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**SCIENTIFIC BASES
OF
AIRPLANE, PROJECTILE, AND MISSILE DEVELOPMENT**

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Director, National Advisory Committee for Aeronautics**

**(Paper to be presented before American Ordnance Association,
New York, December 7, 1955).**

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Introduction

It is a great pleasure to join in honoring Robert H. Kent with whom I have been associated to some degree for the past 30 years. Kent began scientific work in ballistics at a time when the art of ballistics measurements and the theory of the motion of projectiles were in a state that we now consider very primitive. He made original contributions to both fields. His many reports deal with practically every aspect of ballistics-- interior, exterior, and terminal -- and with the design and performance of weapons. His contributions reflect extensive knowledge of physics, mathematics, and engineering as well as mature scientific judgement and originality of approach. He has interpreted the results of his scientific work in terms understood by the designers of projectiles and accordingly many of our latest projectiles embody the results of his experience, measurements, and advice.

As my contribution to this Kent Seminar on the Scientific Bases of Weapons I have elected to speak to you about some of the scientific aspects

of weapons which travel through the air in order to accomplish their mission. The use of missiles which are in themselves destructive because of their mass, speed, and shape dates back to antiquity. The term ballistics is derived from the Roman "ballista", a machine for throwing stones against the enemy. With the invention of the gun and gunpowder, the missiles became round balls of iron and steel. Such missiles were propelled with the speed of sound as early as the year 1644. Later the missiles were developed into aerial vehicles for transporting charges of high explosives to the target as in artillery shells.

The largest such aerial combat vehicle is the airplane which transports means of destruction to large distances, becoming a platform from which gun-launched projectiles are fired, bombs dropped or guided missiles released. The most modern aerial vehicle is the guided missile which may take the form of a projectile carrying its own means of propulsion or of an unmanned airplane. In its design the ancient art of ballistics and the modern art of aeronautics merge into a single discipline.

Developments Depend on Scientific Knowledge

The development of projectiles, airplanes, and guided missiles involves the application of the same scientific principles to the design of the aerial vehicle itself. In each case the motion of the vehicle is in accord with the classical equations of mechanics for a body free to rotate about any axis and to move in any direction in response to the applied forces. The forces exerted by the air depend on the motion relative to

the air and on the attitude of the vehicle relative to the path of its center of gravity. The study of the forces exerted by the air lies within the province of aerodynamics.

Some form of propulsion is needed for each vehicle, and development of the propulsion system involves applications of thermodynamics and chemistry in addition to aerodynamics and the special field of combustion. For each vehicle the suitable selection of materials and the attainment of sufficient strength of the structural frame rests on basic scientific knowledge of metallurgy and applied mechanics.

In airplanes and guided missiles there are many applications of electronics in navigation and guidance. For gun-fired projectiles the acquisition of targets and control of the pointing of the gun utilize electronic devices. Finally the destructive effect of the weapon is dependent on the design of the warhead, in which still other fields of scientific investigation are called on for information.

The scientific bases for the development of projectiles, airplanes and guided missiles include nearly all of the physical sciences as well as many fields of applied science and technology. A brief paper cannot hope to describe this extensive foundation even in outline. It can only give illustrations of the common scientific bases of the design of the several weapons as aerial vehicles.

The Forces Resulting from Motion through the Air

The first concept of the effect of air on the motion of a projectile was the simple one that the air offered a resistance to motion through it. This resistance or drag force was assumed to be applied in the direction opposite to the direction of motion of the projectile. A large part of ballistics down through the first World War and to some extent even today is based on this simple assumption. Many ballistic tables are based on the idealized spherical particle subject only to a drag force.

Aeronautics on the other hand from the beginning utilized wings which derived from the motion through the air a lifting force of sufficient magnitude to support the weight. The drag force was balanced by propeller thrust. Observed motions of aircraft and the results of wind tunnel measurements led to a resultant force with three components along three reference axes and three moments of the force about these axes. At first the force system was considered as a function of the attitude of the vehicle and the relative air speed but it was soon found that the forces and moments depend also on the angular velocities about the three axes.

As ballistic observations became more refined and in particular when spinning projectiles came into general use, it was observed that motions were present corresponding to aerodynamic forces and moments in addition to the drag. Thus ballistics also arrived at essentially the

same complete force system and developed methods of computing the force system from refined scientific measurements on projectiles fired through the air on special test ranges.

Robert H. Kent published many reports on the force system on spinning projectiles and on the analysis of range firings to determine the force system. With Hitchcock he made the first determinations of the increase in drag due to projectile yaw. He analyzed spin experiments to compute spin-retarding torque coefficients and their relationship to skin friction. He introduced dimensionless drag coefficients into ballistics during 1937 in conformity with modern aerodynamic practice. Today as a result of the work by Kent, together with that of many others, ballistic and aeronautical data may be given a unified treatment.

Supersonic Wind Tunnels

Wind tunnels were first developed to meet the needs of aeronautics, the first by F. H. Wenham in 1871 for the Aeronautical Society of Great Britain. Through the years the speeds of wind tunnels have increased somewhat in advance of the speeds of airplanes from the subsonic to the supersonic range. However, the supersonic wind tunnel was invented to meet the needs of ballistics. P. Salcher, an associate of Ernst Mach, the Austrian scientist whose name is now used as an index of speed, suggested the use of an air jet to study shock waves around a projectile. This forerunner of the supersonic wind tunnel

was very tiny, the first supersonic jets ranging from one-twentieth to one-fifth inch in diameter. During World War I French scientists made measurements on projectiles in a supersonic wind tunnel with a De Laval throat 3.15 inches in diameter.

Shortly after World War I, L. J. Briggs and his associates made measurements on projectiles in a 12-inch open jet at subsonic and low supersonic speeds. As a member of that group I well remember Kent's scepticism about the value of wind tunnel measurements on projectiles. The quantitative results did not agree with his free-flight measurements, although the qualitative results were similar. The funds available for supersonic research at that time did not permit construction of air streams which were sufficiently large to give reliable quantitative results.

The development of supersonic wind tunnels in Europe received great impetus from the Volta Congress on High Speeds in Aviation held in Rome in 1935 under the sponsorship of the Italian government. Germany took the lead and, by the end of the war, had under construction at Kochel a 76,000 horsepower supersonic wind tunnel, 3.3 feet square at the working section, for Mach numbers up to 10.

In the U. S. a 24-inch intermittent flow wind tunnel was built by John Stack in 1933 at the NACA Langley Laboratory. No additional supersonic facilities were built for several years. Th. von Kármán proposed in 1939 that the Ordnance Department of the Army build a

supersonic wind tunnel for aerodynamic measurements on projectiles. This proposal was debated for several years, and a model of the tunnel was built by the California Institute of Technology. A 15- by 20-inch wind tunnel of 13,000 horsepower was finally authorized, built under Kent's supervision, and began operation in December 1944.

Before the end of the war the National Advisory Committee for Aeronautics had in operation two supersonic wind tunnels for aeronautical research. Three additional larger facilities began work in 1948 at speeds up to twice the speed of sound. At present the U.S. is placing in operation large supersonic wind tunnels, with dimensions from 4 to 16 feet, speeds up to five times the speed of sound, and powers up to 250,000 horsepower.

Test Ranges

When Kent began his scientific work, the chief testing tool of the ballistician for studying the flight of projectiles was the proving-ground range. The projectile was shot through wire grids and cardboard sheets, the first used with the Boulen^gé chronograph to measure speed, the second to determine the angular inclination of the projectile to its flight path (yaw angle) from the shape of the hole left in the card. Kent studied the effect of the yaw cards on the motion. He introduced the solenoid chronograph which measured speed without interposing wire grids in the path of the projectile.

Like wind tunnels, ranges and range techniques have been highly developed as tools for aerodynamic measurements. The proving ground ranges have become more useful through great improvements in photo-theodolites and cinetheodolites and radar techniques of measuring position and speed. Instruments such as accelerometers, angular velocity and attitude meters, etc. have been mounted directly in aerodynamic models or actual missiles with their indications transmitted to the ground via radio. Modern proving grounds are essential development tools for weapon development.

For research purposes, instrumentation development has permitted the use of shorter indoor ranges. Spark photography and electronic timers have permitted measurements of sufficient accuracy to obtain the principal aerodynamic parameters. Ranges have been built in which the air pressure could be varied, increased to give higher effective scale of the model, or decreased to simulate high altitude. Ranges have been combined with wind tunnels to obtain higher relative speeds between model and air.

Theory vs. Experiment

The preceding discussion has emphasized the experimental approach to aerodynamics, since this has in the past been more productive in producing information immediately applicable in weapon design. Theoretical computations have been useful in the early stages of design of subsonic aircraft and there is every evidence that

compressible flow theory is useful to designers of supersonic aircraft and guided missiles. Application to gun-launched projectiles and rockets has been limited, partly because of the drastic limitations on shape and partly because the effects of the air forces are in the nature of perturbations of the vacuum trajectory.

It is important that the applicability of available theories be checked by suitable experiments and that the assumptions made in the theoretical treatments be made in the light of experimental data. The ideal procedure is a suitable balance between the theoretical and experimental work.

The Stability Problem

Perhaps the most difficult technical problem in the development of aerial vehicles is that of securing stable flight through the air, i. e. flight without tumbling or large oscillations in the attitude of the vehicle with respect to its trajectory. Robert Kent has long been associated with work in this field as applied to projectiles. Many in the audience will recall the three models with which he demonstrated instability, stability, and super-stability of spinning projectiles.

In aerial vehicles without tail surfaces the resultant air force passes in front of the center of gravity and thus causes the vehicle to rotate to a large angle or even tumble. This tendency may be overcome by fins at the rear but it is difficult to obtain stability by fins wholly contained within a tubular launcher such as a gun or mortar. One

solution is the use of folded fins which extend after the missile leaves the launching tube. The older and more common solution is to spin the missile rapidly about its axis, so that gyroscopic forces convert the upsetting motion into a stable motion in the vicinity of the flight path. The condition for stability is that the axial moment of inertia and spin rate be large in relation to the transverse moment of inertia and the aerodynamic upsetting moment. It becomes increasingly difficult to spin-stabilize a missile as the length is increased in comparison with its diameter as in a long rocket.

Airplanes, bombs, and guided missiles are stabilized by the use of suitable stabilizing surfaces or fins. By a suitable disposition of surfaces, the aerodynamic moments about the center of gravity may be balanced. The stability problem is then to also insure that when the steady motion is disturbed by wind gusts or otherwise that the vehicle returns quickly to its original attitude. The mathematical theory of the dynamical stability of aircraft was given in essentially complete form by G. H. Bryan in 1911. The problems of stability and control of current and future aircraft and missiles are describable in the same conceptual framework, although speeds have increased from 100 to more than 1,000 miles per hour. There are, however, great changes in what Bryan described as the "approximations to the air pressures on the planes and other parts."

A casual reader of the ballistic and aeronautical literature might gain the impression that the stability problems of spinning projectiles and of aircraft are fundamentally different. It is however possible to give a unified set of equations applicable to all aerial vehicles and this has recently been done by A.C. Charters, a former associate of Kent, in NACA Technical Note 3350. A further demonstration of the essential identity of the problems was given by a puzzling divergence from steady flight encountered by modern fighters when rolled rapidly about a longitudinal axis. This particular instability turned out to be familiar in ballistics, being associated with the near coincidence of rate of roll and period of oscillation of the airplane or missile about the axis of yaw or pitch. This type of instability lasts only while the airplane or missile is rolling. The unified treatment shows that it is not always possible to stabilize a projectile by spin and a sufficiently high rate of spin is likely to destabilize finned projectiles and airplanes, although if certain conditions are fulfilled a finned projectile or airplane may be stable regardless of spin.

The general stability problem is one of designing the airplane or missile to possess satisfactory oscillation characteristics without compromising other performance requirements. It is becoming apparent that purely aerodynamic means may not be adequate over wide ranges of speed and altitude. Thus automatic stabilization is being applied to many modern aerial vehicles. Thus a gyro instrument may be used to

detect changes in the directional motion, and transmit the information to a servomotor which moves a rudder so as to damp the motion.

Propulsion

Another field to which Robert Kent contributed is that of interior ballistics which is the ballisticians' name for the propulsion problem for projectiles fired from guns. The aerodynamic design of gun-fired projectiles must generally be completely subordinated to the demands of the propulsion system. There are drastic limits on size and shape and mechanical strength. In addition external roughness in the form of rotating bands and bourrelets and the large flat base are aerodynamically undesirable. The possible configurations are aerodynamically unstable, although fin stabilized missiles with folding fins have found application in some weapons.

The ballisticians' fuel has progressed from gun-powder to various modern propellant powders. Missiles were fired from guns at supersonic speeds about 300 years ago. Current projectiles fired from guns weigh from a few pounds to more than one ton and travel at speeds up to a little above twice the speed of sound. The German long-range gun fired a 265 pound shell at a muzzle velocity of about four times the speed of sound. Its range was about 75 miles whereas 20 or 25 miles is the more common maximum range.

The coming of the rocket has removed many of the limitations on the shape and size of aerial vehicles for weapons. By carrying the gun

barrel on the vehicle, using its recoil for propulsion, and continually renewing the fuel charge by liquid injection, smaller accelerations may be used, thus permitting lighter structures. The vehicle may embody such aerodynamic refinement as is needed to reduce its drag and to obtain stable flight. The performance capabilities were dramatized by the German V-2 rocket which carried a payload of one ton to a distance of 180 miles at a speed which reached five times the speed of sound.

The combustion problems of the fuel in guns and in rockets have much in common. In each case one seeks controlled burning, fast but at a more or less uniform rate, without violent instability which may produce structural failure. The study of combustion in its broadest aspects is fundamental to the design of satisfactory propulsion systems.

For some weapon applications there is advantage in utilizing the atmospheric air rather than oxygen embodied in the chemical fuel. This advantage is found in the ram jet which is well suited to take up the task of continued propulsion within the atmosphere after the vehicle is launched by a rocket engine. For airplanes and for some missiles the turbojet engine proves most effective. Thus again the guided missile brings together the propulsion developments of ballistics and aeronautics and opens the way for new types of weapons.

Weapon Systems

Aerial vehicles are not in themselves weapons. They must be provided with suitable means of destruction either directly in the form of high explosive or fragmentation warheads or indirectly in the form of subsidiary missiles or projectiles carrying warheads. Launching devices; navigation, aiming, and guidance equipment; gun sights and other fire control equipment; communication devices; target detection radars ---- these are some of the other essential physical components of a complete weapons system. Many scientific fields contribute to the development of these components, and there are specialized areas of applied research, for example, terminal ballistics, of unique significance for the design of effective weapons.

In the final analysis the various components must be integrated into a complete system whose performance is optimized. The building of a modern high speed aircraft or missile has necessitated and brought into being a new concept of functional coordination and system analysis, in which many groups of professional specialists have joined talents to produce results beyond the ability of any single man or group.

Research, the Foundation

Weapon system development thus rests upon a broad base of scientific knowledge, the results of fundamental and applied research. On the extent and soundness of this foundation depends the final quality of our weapon systems. Just as the foundation of a building is not

easily visible when the structure is completed, so the research behind a new weapon is not easily seen in the completed weapon. By then the basic research done some years before is no longer new and is replaced in the public eye by the research of today which is the foundation for tomorrow's weapons. The development of weapon design to its present state would have been impossible without accompanying advances in scientific research. Each new weapon is the embodiment of many research results in many fields. Its ancestry leads not to a single research project but to many carried out at many institutions and even in many countries. The base of the pyramid is very broad.

Robert Kent and your speakers this afternoon are workers on this hidden foundation, the broad scientific basis of weapon systems which the designer utilizes in the art of creating new and improved tools for our military services.

The foundations must be broadened and deepened to support future advances. Research must look beyond the immediate problems and seek understanding. In many areas the immediate applications may not be apparent. But experience teaches us that a stockpile of scientific information obtainable from a vigorous program of basic and applied research in the underlying scientific fields is essential to system design. Only with adequate knowledge can the design of an aerial vehicle, for example, be accommodated to the design of guidance and warhead, to give good overall performance.

The research programs in the sciences basic to weapon development need the interest and support of informed citizens. In particular there must be a greater awareness and support of the longer range programs of basic research, which constitute the supply of material not only for swords but for pruning hooks as well.
